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A Prototype System for using Multiple Radios in Directional MANET (Mobile Ad Hoc Network)

A NISE funded Applied Research Project

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EXECUTIVE SUMMARY

The performance benefits of using high-gain steerable directional antennas for wireless networks are well known. They include spatial reuse, higher data rates, longer range, low probability of interception and detection (LPI/LPD), and anti-jam capabilities. This performance is desired for backhaul, line of sight (LOS), beyond line of sight (BLOS), and other tactical-edge wireless networks. From a practical stand point, it is difficult to employ directional antennas in a mobile ad hoc network (MANET) as most current radio and wireless networking protocols were designed for use with omnidirectional antennas. The fast beam switching of electronically steerable directional antennas represents a physical layer change, and therefore introduces instabilities to many protocol layers of a networking system that are unaware of and unable to quickly adapt to physical layer changes. The Multiple Radio per Node Network Architecture (MRNNA) makes it is possible to use electronically steerable directional antennas in a MANET in a radio agnostic way by building networks out of dedicated point-to-point links. This document presents a protocol that accomplishes these goals.

CONTENTS

Figures

1. INTRODUCTION AND BACKGROUND

The power of the Multiple Radio per Node Network Architecture (MRNNA) comes from its use of multiple radios, each with its own directional antenna. The benefits that this provides come in two categories:

1. Performance benefits that are derived from the ability to create multiple links per node and the ability to minimize interference through both spatial reuse and frequency separation: Since each link may be used concurrently at its full link capacity, total network throughput will be greatly increased compared to single radio systems and/or systems that use omnidirectional antennas.
2. The benefit of being radio agnostic: Previous work in directional wireless networks has focused on developing new protocols that are aware of the physical layer changes caused by beam steering. The difficulty in this approach is the tremendous amount of complexity in synchronizing the functions of the medium access control (MAC) protocol, routing, quality of Service and beam steering all operate on different time scales. The protocols that have come out of this research are inefficient and non-existent in commercial radios. Since MRNNA networks are built out of dedicated point-to-point links, only small changes to the physical layer needs only small changes, which occur on larger time scales. Therefore, standard radio protocols can work as is with no modifications. A caveat of this is that convergence times of wireless routing protocols have an impact on network performance just as in other wireless networks. Since the MRNNA protocol has perfect knowledge of the topology it would be easy to synchronize this with the routing layer.

As described earlier, prior research has focused on modifying network and radio protocols to support directional antennas. The paper in [1] recognizes the shortcomings of directional MACs and proposes a more practical solution that involves attaching a single radio to multiple-sector antennas and then selectively switching on or off the antennas to form topologies. Such a system could be considered “radio agnostic” as it allows the use of unmodified MAC protocols. However, as a single radio system it does not fully exploit the power of building multiple dedicated links and also provides limited support for mobility. References [2], [3], [4], [5], [6], [7], [8], [9], [10], and [11] describe directional MACs.

The Defense Advanced Research Projects Agency (DARPA) Wireless Network after Next (WNaN) radio is an example of a radio with multiple transceivers that can manage performance frequency to form topologies and get performance gains from the reduced interference due to frequency separation. The WNaN radio was not designed to work with directional antennas but it potentially could be made to work with Directional Ad-hoc Networking Technology (DANTE)/MRNNA technology with some effort.

A previous paper describes the MRNNA and the technical issues with using directional antennas [12]. In this report, we follow on that work and present a link selection protocol that we have implemented in a prototype system using unmodified wifi radios and electronically steerable DANTE antennas developed at SPAWAR Systems Center Pacific (SSC Pacific). We will discuss the functions of each component as well as the message types that get passed between components and how they coordinate to form a topology. We will also discuss radio issues and describe the basic control that is required to use a different radio.

2. MRNNA SYSTEM OVERVIEW

A MRNNA network node has a central master controller (MC) that connects to multiple sectors. Each sector contains a single-board computer, a radio, and a directional antenna. Figure 1 shows a diagram of a MRNNA network.

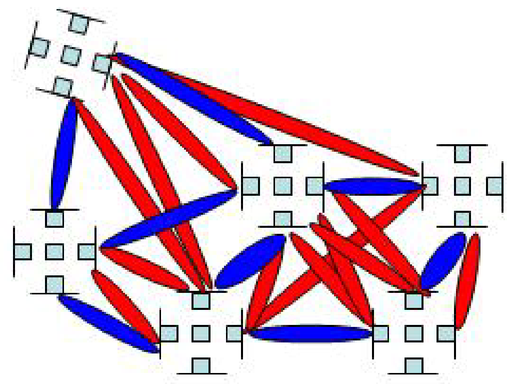

Figure 1. MRNNA network diagram.

The above diagram shows how it is possible to form many different physical topologies in this architecture by pointing beams in different directions. As nodes move around, different choices need to be made about which links are selected as “dedicated” links and which are ignored. The question of what is the best physical topology arises, and the answer to this depends on the goals of the network. Are you trying to maximize throughput between a specific pair of privileged nodes? Do you want to provide more robust topologies that are more tolerant to link failures? The MRNNA provides a rich set of topology choices, and many different link selection algorithms may be developed and tailored to specific networks.

Once a topology is selected, the configuration of links will be maintained for as long as possible to provide the stability that allows higher layer radio protocols to function. Furthermore, the links may be moved to different frequencies that reduce interference and allow each link to operate at its full capacity. Frequency selection can be treated as an edge coloring problem for which polynomial time approximation algorithms exist. However, to minimize interference, treating frequency selection as a pure edge coloring problem is impractical as it ignores real-world radio-frequency (RF) phenomena such as antenna side lobes, multi-path bounces, and excessive transmit power. A form of interference detection must also be considered to mitigate these effects. Power control is an option to reduce interference but it is not something we currently consider, as its usefulness really depends on the specific RF environment where the network operates. Much of our prior work has been on establishing and maintaining long-distance links on moving platforms over water. This is an already challenging RF environment where it is common to see 20+ db fades that occur on short time scales due to the “sea bounce.” In this type of network where the nodes are physically distant from each other, the interference due to antenna side lobes and excessive transmit power are less of an issue. In networks where the nodes are physically closer together, transmit power control may provide more of an interference reduction benefit.

For this prototype system, we built seven MRNNA nodes and mounted them on movable carts. Figure 2 demonstrates a six-sector node with a staggered triangle design. Using these carts, we can move nodes around and see how they make the correct topology decisions. The rest of the report describes the function of each component and how they all work together.

Figure 2. Six-sector mobile node.

3. SECTOR CONTROLLER FUNCTION

The main functions of the sector controller is to (1) control the beam steering of the antenna to point in the right direction, (2) send/receive HELLO messages in each direction of its coverage area, (3) obtain link-state information from the radio and report it to the master, and (4) perform state transitions and link establishment/maintenance operations as instructed by the master. The operational states of the sector controller are as follows:

1. Discovery. During discovery, the sector controller will sweep through the beams of the directional antenna and transmit HELLO messages at each beam position for remote nodes to hear. HELLO messages contain a local node identification as well as geo-location information. When a sector controller receives a HELLO message from another node, it will use this node ID to obtain link-state information from the radio and report the link to the master controller.
2. Link Establishment. When the master decides that a sector should form a link with a remote node it sends an LE0 message to the sector instructing it to establish a link with a specific remote node. A sector controller in the LE0 state will begin broadcasting messages to the remote node offering to create a link. If a remote sector receives this message and it has also been instructed by its master to link up, it will respond with an LE2 message that is an agreement to create the link.
3. Handover. Due to mobility, it is often required to hand over a link from one sector to another. The procedure for this is rather simple. Once the MC runs its topology control algorithm and determines that a handover is necessary, it will inform the new local sector to pick up the link with the remote sector. It will also inform the currently tracking sector that a handover is pending and it should be prepared to change states. The reason it needs to inform the currently tracking sector of the handover is to avoid

race conditions and miscommunication in the rare case that both nodes decide to hand over at the same time. This is what we call a "double handover."

4. Tracking. This is the state after a sector controller has established a dedicated link with a remote sector and focuses on steering the beam to maintain the health of this link. It may also coordinate a frequency switch with the remote sector at the instruction of the MC.

To use a different radio in the MRNNA node, the sector controller must be modified so that it can automatically talk to the new radio using its provided control interface. The extent to which this is possible varies from radio to radio. The minimum set of controls the sector controller needs is for the radio to be capable of switching frequency and receiving link-state data such as Received Signal Strength Indicator (RSSI) and Link Quality.

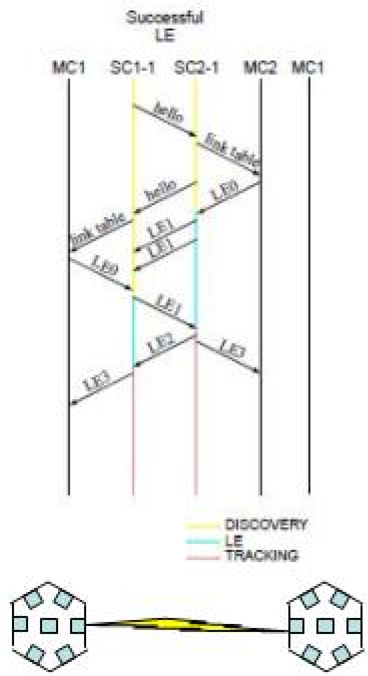

Figure 3. Message sequence for establishing a link between sectors.

4. MASTER CONTROLLER FUNCTION

All topology control decisions are made at the master controller. Each MC is connected to multiple sector controllers from which it receives link-state information and geo-location information of remote nodes in the area. The MC also exchanges/forwards link state and positional information with other directly connected MCs. The MCs use this information to build an adjacency matrix of all possible links that may be formed in the network. After exchanging tables, all MCs will have an identical picture of what the network looks like. Since they all run the same link selection algorithm, each MC will compute the same topology for the network. Each MC then examines what the overall network topology should be and compares that to its current local state to see if it needs to effect any local changes. To execute local changes, the MC assigns its sectors to the appropriate new state and the sector executes the change. For example, if the MC detects that its local sector number two should be linked to remote node three, it will send a link establishment message to the local sector and the local sector will attempt to establish a link to a sector on the remote node. A sample timing diagram for the full link establishment sequence is in Figure 3.

5. LINK SELECTION PROTOCOL

The link selection protocol has gone through three major revisions in its development. The first iteration was named Greedy Local Link Selection (GLLS). In this version, the master controllers made decisions about which links to select based solely on local information. It identified the remote node and sector based on information embedded in the beacons and associated an RSSI reading for each remote sector. On each loop, it sorted the links based on signal strength and assigned its local sectors to track a specific node based strictly on which ones had the highest signal strength. This algorithm was simple in the sense it takes a greedy approach and uses local information only. This worked well for networks of up to three nodes but instabilities surfaced after adding a fourth node. The issue was that no coordination existed among the nodes. Something simple such as a sector sweeping through its beams causes changes in the physical layer. The other nodes would notice the change and not understand what caused it. Since no coordination existed, the nodes were constantly reacting off of each other and the network would become unstable. The other issue is that asymmetric links would often appear.

The next version of the protocol was the GLLSI. The new feature in this protocol was the concept of “pair bonding” where specific sectors of two nodes would communicate and agree to pair up. This added stability to the network. The new problem with this approach was that it still did not consider the entire network when making its link selections. It used local information and information obtained from its one-hop neighbor. Through mobility, many complex scenarios emerged in which the nodes did not have enough global information to make a proper decision.

This led us to the MST-6 algorithm in which the MCs exchange information with each other so that they all have a common picture of the network at a point in time. With a common picture of the network, they can each independently compute the same topology of what the network should be. As previously mentioned, many different link selection algorithms may be used, and the best one depends on the network. As a base case, the nodes connect a minimum spanning-tree using link distance as a metric. Then we add as many links as possible to fill out the network.

6. NETWORKING

One of the main benefits of the MRNNA architecture is the separation of physical topology decisions from the MAC layer and routing protocols. However, use of multiple radios can potentially complicate the job of routing protocols as there may be a much larger number of paths between nodes. Each node has six sectors and a master controller, each of which is a networking device. The main choice to be made is whether to run an instance of a routing protocol on the sectors or to put them in “bridge” mode. Running an instance of a routing protocol on the sectors increases the number of routers on the network by a factor of 6, which dramatically increases the volume of protocol messages and also increases convergence time. Therefore, bridge mode is the obvious choice.

When the routing protocol chooses a different path than the one chosen by the topology manager, one issue that surfaces is the presence of multiple links between nodes. This can occur when nodes are close enough together to reach each other using the side lobes of the antenna. To achieve full performance of the MRNNA, it is necessary for the routing layer to choose the same link as the topology control since that link will be actively maintained by the topology manager and will be at a frequency that is isolated from the rest of the nodes. To achieve this, it may be necessary to implement some limited cross-layer communication between the topology manager and the routing protocol. Another area where a cross-layer would be beneficial is to adjust routes quickly in response to a sector-to-sector handover.

We have tested both the Open Link State Routing (OLSR) protocol and BATMAN-ADV (better approach to ad-hoc networking - advanced) in a four-node MRNNA network. Both worked and performed similarly. Typically, there was a delay of 4 to 6 s for the protocols to adjust to topology changes. This delay is present upon establishment of a new link and more noticeable to the user on sector-to-sector handover where connectivity may cut out until it re-converges.

7. PERFORMANCE TESTING

As previously mentioned, MRNNA performance benefits come from the ability to use multiple links between nodes concurrently. We demonstrated this concept in a static lab test performed with five nodes (Figure 4). The number of radios we had on hand limited the node count for this test. Figure 5 shows test results for two runs using off-the-shelf wifi radios. The first run uses a single frequency, so all radios had to compete for access to the channel. As expected, the throughput per node drops as we add nodes to the network. The second run uses a different frequency for each link and therefore can use them concurrently. The throughput per node increases as you add nodes to the network. Throughput per node will not continue to increase like this forever. It really depends on node density, the number of radios per node, and the number of available frequencies. It will be interesting to run some experiments using a higher node count to see how far this scales. This test certainly shows the immediate benefit that is available to smaller MANETs such as in Navy ship-to-ship LOS networks.

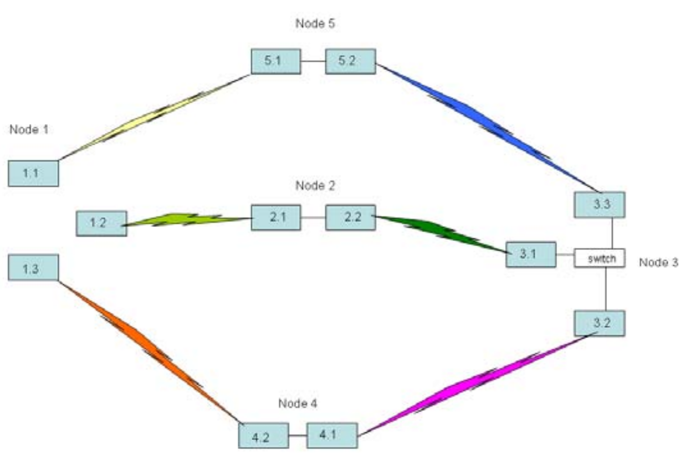

Figure 4. Five nodes with multiple radios on different frequencies. Note that it would be possible to add additional links without increasing node count, which would show a more dramatic performance increase.

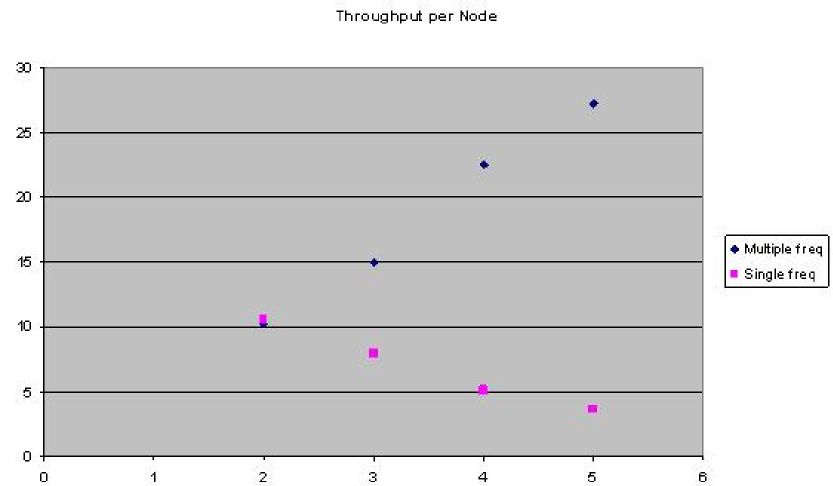

Figure 5. Results of running iperf on each link. Throughput per node is calculated as aggregate throughput divided by the number of nodes.

8. CONCLUSION AND FUTURE WORK

It is possible to field a mobile ad hoc network using directional antennas modifying wireless network protocols by using the MRNNA approach, and many different topologies formed. The question then arises about what is the “best” topology. The answer to this really depends on the overall structure of the network and knowledge of which traffic flows are more important than others. Many optimization problems may surface such as choosing a topology and selecting multiple routing paths to maximize throughput between a pair of nodes. Although it is desirable to avoid cross-layer design, there are instances where some cross-layer communication between the topology control function and the routing layer minimize traffic interruptions after executing a change in physical topology.

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14. ABSTRACT

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